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Potential Role of Aerosols

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CLIMATIC TRENDS OVER NORTH AMERICA: Potential Role of Aerosols

by

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ABSTRACT

The spatial pattern and the trends (1948-1980) of several key climatic parameters show that there has been a reduction of the surface noon temperature over the S.E. United States. During the same time, and over the same region, there has been an increase of dewpoint, relative humidity, and noon cloud cover. The region over which these changes occured coincides with the region of most significant increase in haziness (aerosol concentration). However, a cause-effect relationship has not been established.

INTRODUCTION

It has long been recognized that the amount of solar radiation reaching the surface of the earth is an important climatological variable. Abbott (1911) and others demonstrated the near constancy of the amount of solar radiation reaching the outer limits of the atmosphere-as is implied by the use of the term "solar constant." Indeed, study of solar variability as a cause of climate change is still an active field of research. However, the variations in radiation reaching the surface of the earth are to a much larger extent due to fluctuations in the transmission through the atmosphere than to the variations of the solar constant itself. Aerosols, along with clouds, ozone, air and water vapor are the key factors determining the transmission.

McCormick and Ludwig (1967) and Bryson (1968) argued that a buildup of atmospheric aerosols could have the effect of increasing albedo, thereby cooling the earth. Charlson and Pilat (1969) suggested that since particles can both absorb and scatter light, particles could either heat or cool the earth, depending on the relative amounts of absorption and scattering. Atwater (1970) discussed factors governing the sign of the change in the planetary albedo caused by presence of aerosols, showing that either heating or cooling could result. Of particular importance is the albedo of the surface under an aerosol layer. Mitchell (1971) also noted the roles of both scattering and absorption, with similar conclusions depending on albedo, but with some adjustment for evaporation of water at the surface. Ensor at al. (1971) developed a model that allowed the imaginary refraction index to be varied, concluding that large ambiguities exist due to a lack of data on the absorption and scattering properties of aerosols. Reck (1974, 1975, 1977) explored a variety of the parameters that are imbedded in models of the influence of aerosols, suggesting that aerosols cool the atmosphere, reduce convection and increase planetary albedo.

Aerosols also have an influence on the optical properties and microphysics of clouds. Increases in pollution aerosol lead to increase in the number of cloud condensation nuclei resulting in an increased albedo. Carbon particles are present in rain, snow, and ice, and are therefore expected to be in cloud droplets. The presence of carbon should lead to a decrease in albedo. Hobbs et al. (1974) suggested that pollutants affecting clouds are the most likely to produce modifications in weather and climate.

Robinson (1977), Robinson et al. (1976), and Ball and Robinson (1982) discussed in general the effects of the particulate matter associated with energy production, focusing on surface temperature, planetary albedo and atmospheric heating. A major conclusion was that energy production, e.g., from burning sulfur-containing coal, resulted in a net energy loss from the earth's surface. That is, more solar energy is absorbed in the atmosphere and reflected into space than is released by the burning of coal.

TRANSMISSION OF SOLAR RADIATION

In an aerosol-free atmosphere, about one third of the solar energy passing through a zenith angle of 60^{o} (about 2 air masses) is depleted by Rayleigh scattering, water vapor and ozone absorption even in the absence of scattering and absorbing particles. On the order of 10% of the lost direct radiation is recovered as blue skylight, while another 10% is backscattered to space to give the earth's atmospheric shell its bluish color as viewed from space. The remaining depleted energy heats the stratospheric ozone layer and the near surface layer containing the water vapor.

The scattering, ozone and water vapor absorption processes act on different parts of the solar spectrum as shown schematically in Fig. 1. Furthermore, the atmospheric strata containing the ozone, air and water vapor are also separated. The incoming solar photons first encounter the ozone layer at 10-40 km above sea level. High energy photons in the UV (<0.36 μm) are absorbed in the strongly absorbing bands which, however, saturate quickly with increasing ozone depth. The absorption in the visible band, on the other hand, continues to increase almost linearly with ozone depth.

The second chance for the photon-atmosphere encounter occurs when the solar photons pass through the bulk of the atmosphere. Molecular scattering changes the photon direction mostly at the blue end of the spectrum since the scattering is $\sim\lambda^{-4}$.

A third kind of encounter occurs when the solar photons reach the lowest layers of the atmosphere where most of the water vapor is contained. Water is a major "source" of atmospheric heating via its selective absorption of solar photons in the near IR bands. For water paths >2 cm of precipitable water the increase in amount of solar radiation absorbed is markedly reduced due to the saturation of the main absorption bands.

Typical winter values of precipitable water content of the atmosphere are 0.5-1.0 cm in a vertical column over the eastern U.S.; in the summer it ranges between 2 and 4 cm.

The presence of aerosols in the mixing layer leads to a number of perturbations in the radiative energy balance. The aerosol layer over the eastern United States may cause, on a yearly average, a loss of about 7% of the solar energy which would otherwise reach the ground. About one-half is lost by backscatter to space. The other half is absorbed within the boundary layer with less heating of the ground and more heating of the air in the boundary layer. Heat loss through emission of long wavelength radiation by aerosols may or may not balance energy absorption in the visible wavelengths. If one process dominates the other, the aerosol may lead to either net cooling or a net heating of the boundary layer.

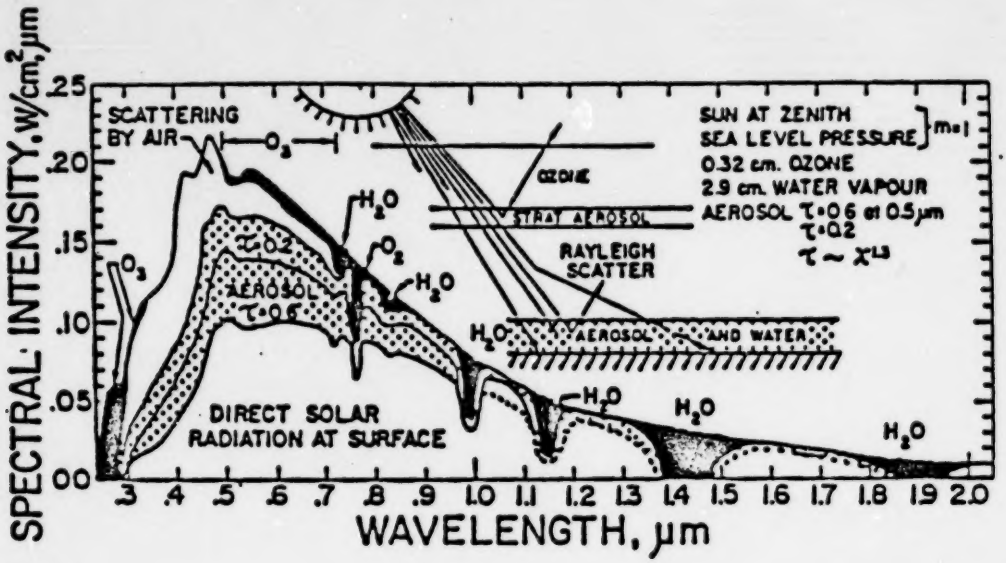

Fig. 1. Illustration of solar radiation spectrum outside the atmosphere and depleted by ozone, water vapor, Rayleigh scattering and aerosol. Parts adapted from Breslau and Dave (1973).

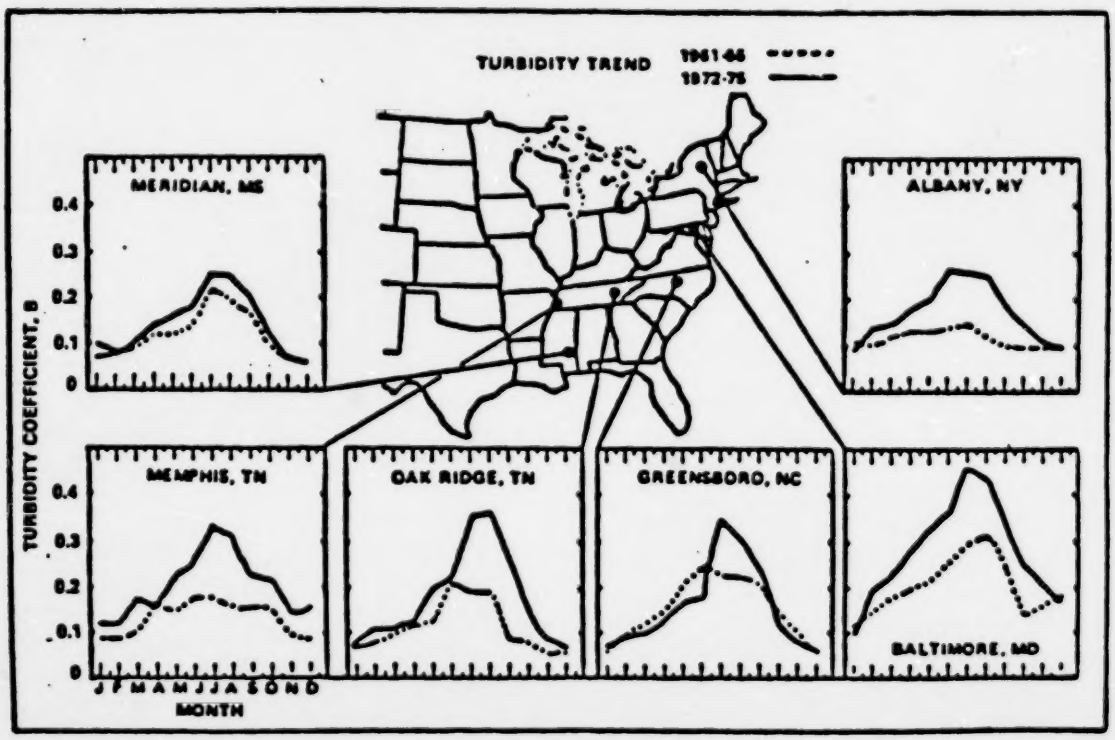

Fig. 2. Seasonal turbidity patterns for 1961-1966 and 1972-1975 are shown for selected regions in the Eastern United States.

TURBIDITY

In the absence of clouds, the intensity of direct solar radiation for a given solar elevation depends on the variable amount of dust, haze, and water vapor in the atmosphere. The extinction produced by these constituents is called "atmospheric turbidity." During hazy episodes, turbidity coefficients as high as 0.6 to 1.0 have been reported, translating into a 75 to 90 percent removal of solar radiation from the direct beam, a 7.5 to 9 percent loss to space, and 7.5 to 9 percent loss in atmospheric heating.

Data from a 29-station turbidity network showed that there are strong spatial and temporal variations of turbidity across the United States. At all sites, the highest turbidity occurs in the summertime and the lowest occurs in the winter, which is consistent with the haziness pattern obtained from visibility observations. The turbidity of the atmosphere in the United States has a strong spatial dependence. In the Southwest, with a mean annual turbidity coefficient of about 0.06, the incoming direct solar radiation is attenuated by only 13 percent, compared with Midwest values of about 20 percent.

The highest turbidity coefficients were observed in the Eastern United States (Fig. 2) where winter values of 0.1 and summer values of 0.2 were typical, meaning that about 20 to 35 percent of the direct solar beam is diverted to sky light, backscattered to space, or absorbed.

In the 1970's, the U.S. turbidity network was expanded under the auspices of the World Meteorological Organization (WMO). In the northern hemisphere there were about 100 operating stations. As with every network, the quality and quantity of data from individual stations are highly variable. The global turbidity network has been deteriorating since 1976, and it is not certain whether it will survive the decade of the 1980's.

TRENDS OF REGIONAL CLIMATE OVER EASTERN U.S.

This work presents the continental scale trends for climatic parameters that are potentially influenced by atmospheric haze and vice versa. The goal was to explore whether any significant regional climatic changes had occurred in the 1950-80 period.

This analysis drew upon a 30-year data base of 3-hourly surface meteorological observations for about 600 stations covering the U.S. and Canada. The data base utilizes computerized weather records supplied by the NOAA National Climatic Center and by the Atmospheric Environment Service Canada. In what follows, the climatic changes will be illustrated for the warm months (July, August, September). This season shows the most significant increase in haziness.

The continental scale maps of local noon surface temperature are shown in Fig. 3. It is evident that since the 1950's there has been a reduction of mid-day temperatures that is most pronounced in the southeastern part of the U.S.

Fig. 4. depicts the average summertime temperature difference between noon and midnight. Here again, it shows a reduction of the daily temperature modulation: the noon-midnight temperature difference is less in the 1970's than in the 1950's.

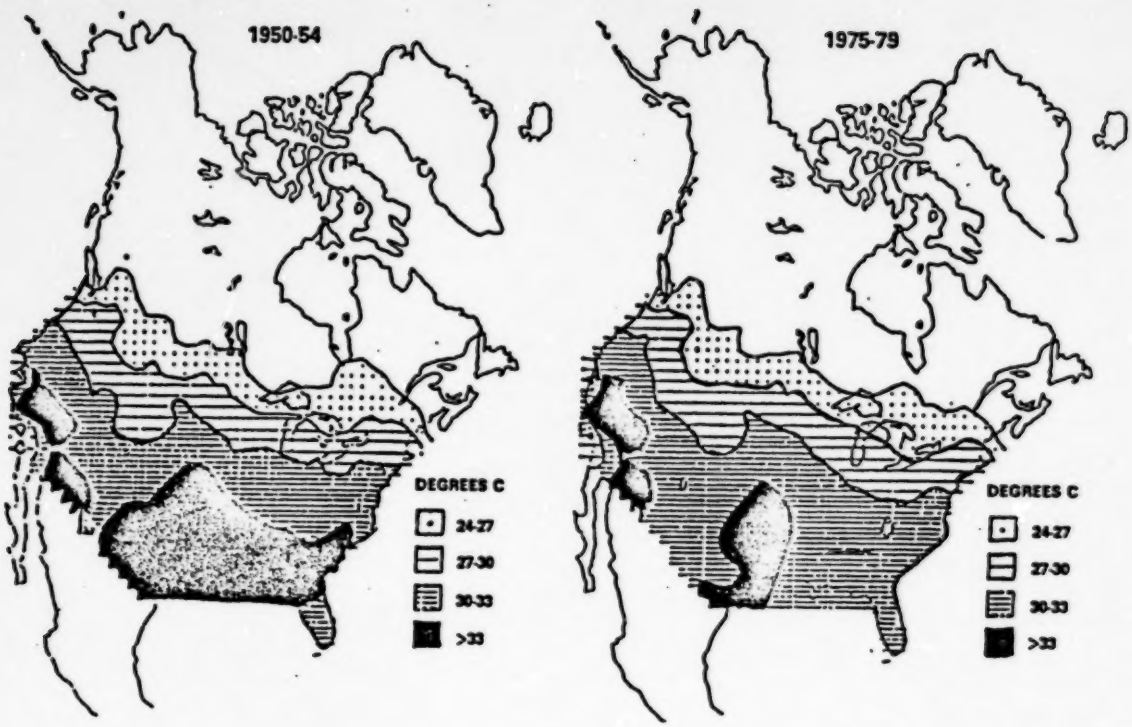

Fig. 3. Noon temperature contour maps. Summer averages (3rd quarter)

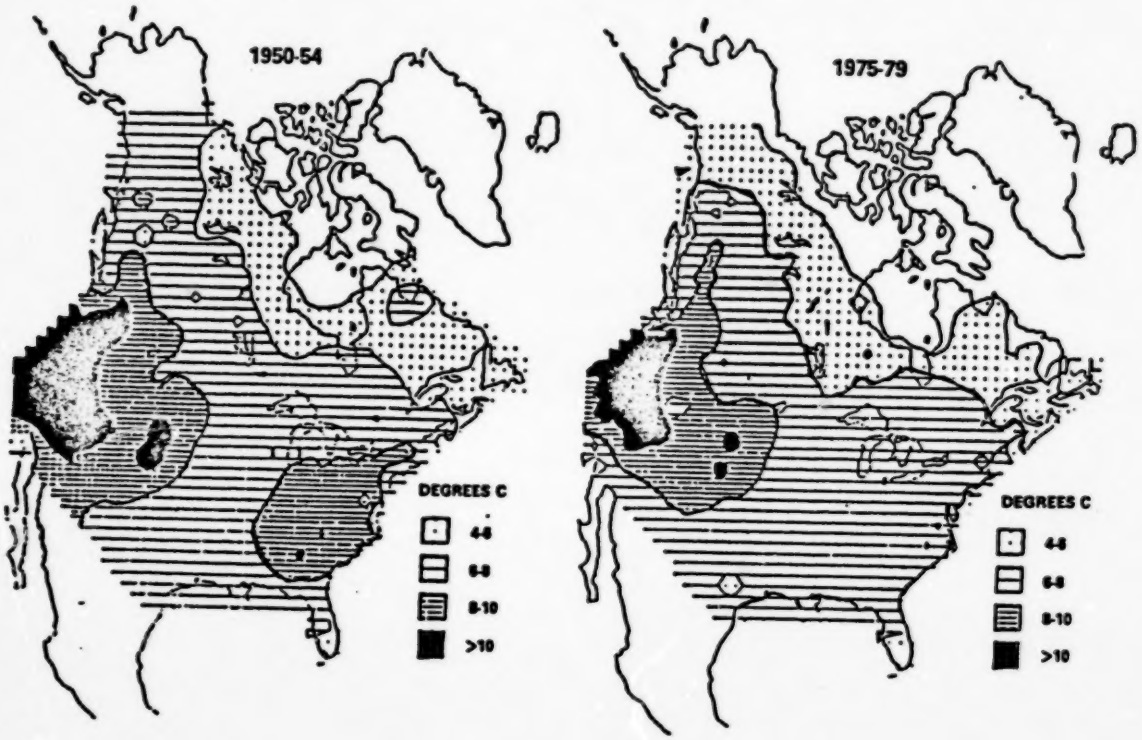

Fig. 4. The average differences between noon and midnight temperatures. Summer season. (3rd quarter)

A climatological map of eastern U.S. noon temperature is drawn for the time periods 1948-52 and 1970-74 (Fig. 5).

The yearly trend of the summer quarter, 1300 hr temperature for a typical Smoky Mountain region site, Charlotte, NC, is shown in Fig. 6 along with the temperature trend of the extinction coefficient.

The most remarkable 30-year climatic change is noted for dew point (Fig. 7). In the 1950's only a narrow belt of the Gulf coast recorded noon average dew point in excess of 20°C. By the 1970's this high dew point belt had expanded several hundred kilometers inland from the Gulf Coast. For the entire eastern U.S. average this resulted in a dew point increase from 16.3 to 18°C. Here again it is worth emphasizing that neither the western U.S. or Canada exhibits such trends. It is thus not likely that experimental or data processing errors are responsible for the trends.

The observed reduction of the noon temperature coupled with an increase of dew point resulted in a substantial increase in noon average relative humidity (Fig. 8). In the 1950's virtually the entire U.S. had a noon average RH below 55%. By the 1970's the entire eastern U.S. exceeded this RH. Thus, on the average, the eastern U.S. noon RH has increased from 54.6 to 60.5%.

Secular trends are presented here for two measures of cloud cover (Fig. 9 and 10). The noon cloud cover reported by the U.S. weather stations refers to the percent of the sky covered by clouds within the lowest 1-2 km of the atmosphere. Canadian surface observations do not contain this parameter causing a sharp gradient at the U.S. -Canadian border (Fig. 9). The noon low level cloud cover east of the Mississippi was 31% and increased to 35% by the 1970's. The increase was again most pronounced in the southeastern states.

The maps of the north American noontime total sky cover are depicted in Fig. 10. The pattern shows an increase from 58 to 63% for the eastern U.S.

The estimation of the low level and total cloud cover is made subjectively by individual observers. It is thus conceivable that an increased haziness of the sky prompted observers to overestimate the sky cover in the 1970's. On the other hand, the increased cloud cover is consistent with the measured increase of atmospheric moisture over the southeastern U.S. If, in fact, the eastern U.S. cloud cover has increased by 5% over the past 30 years, it could explain both the temperature reduction and demodulation.

The observation of fog is again a subjective judgment made by the observers. It generally refers to visual range less than 0.5-1 km. The North American map of reported fog frequencies shows that in the 1950's only the New England states, Quebec and Nova Scotia have experienced fog more than 10% of the time. By the 1970's virtually the entire eastern North America had experienced fog more than 10% of the time. The eastern U.S. average fog frequency had doubled from 7% to 14% of the 3-hourly observations (Fig. 11).

The precipitation frequency is mapped in Fig. 12. It is evident that the rainiest regions are in Canada (>20% of the time), while the least rainy is the arid southwest

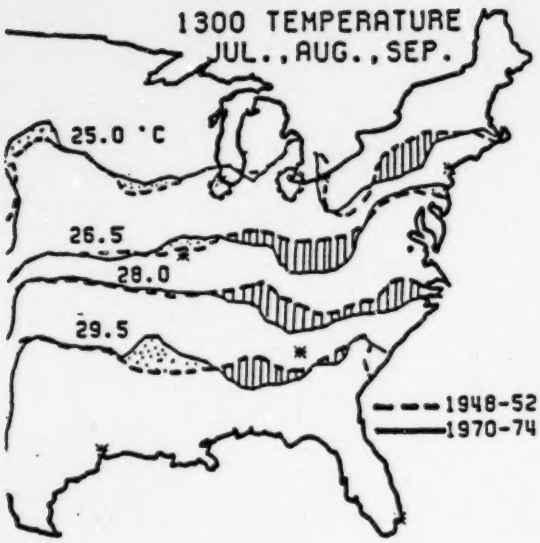

Fig. 5. In the midwestern and east coast regions, the noon temperature contours for 1948-52 and 1970-74 match closely. In the east central U.S. and central New York state, however, the contours shifted southward by 100-200 km, indicating noon cooling (shaded area). The dotted regions represent warming.

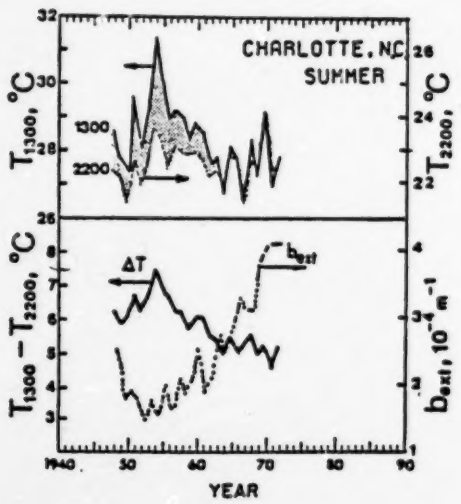

Fig. 6. In the 1950's, the noon temperature was about 6.5°C higher than the 2200 temperature. By the 1970's, the diurnal temperature pattern was demodulated such that the corresponding temperature difference was only 5°C.

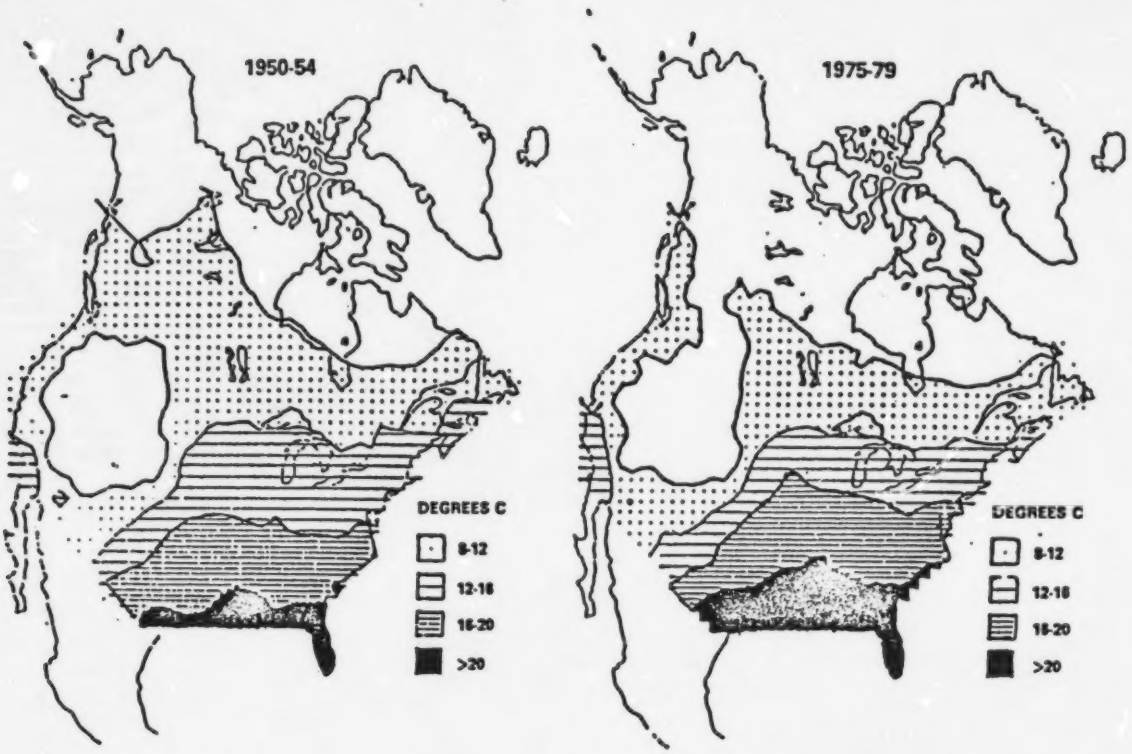

Fig. 7. Noon average dew point in ^{o}C. Summer season. (3rd quarter)

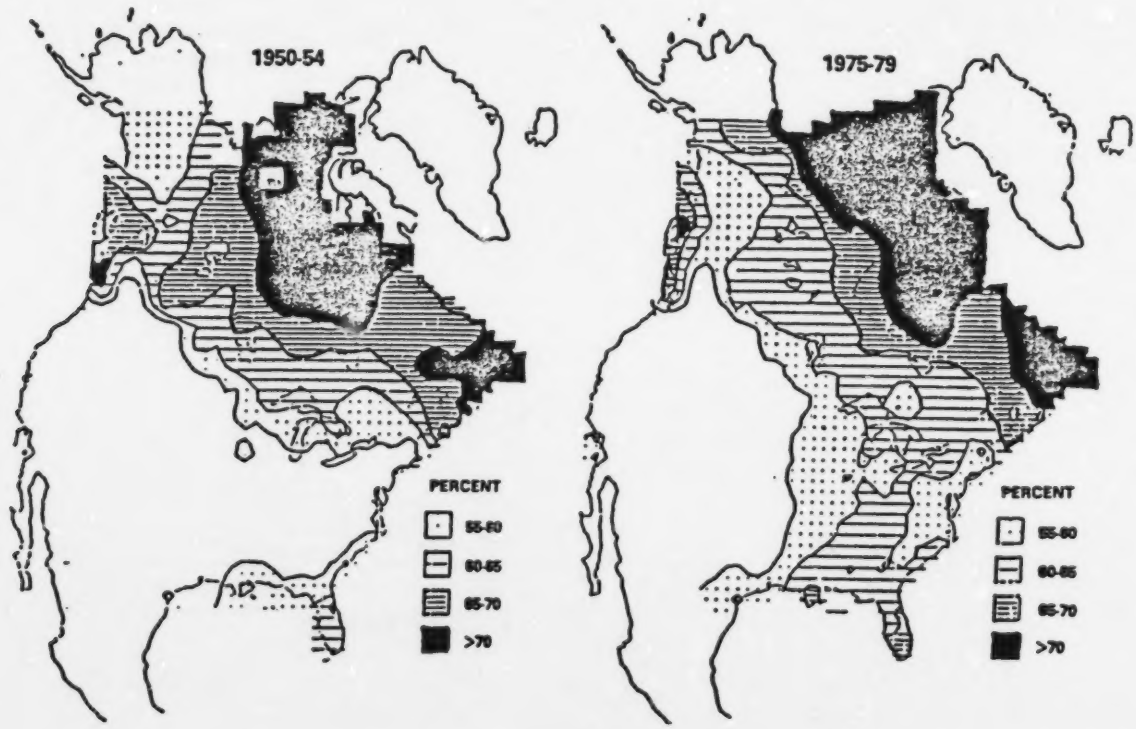

Fig. 8. Average relative humidity. Summer season. (3rd quarter)

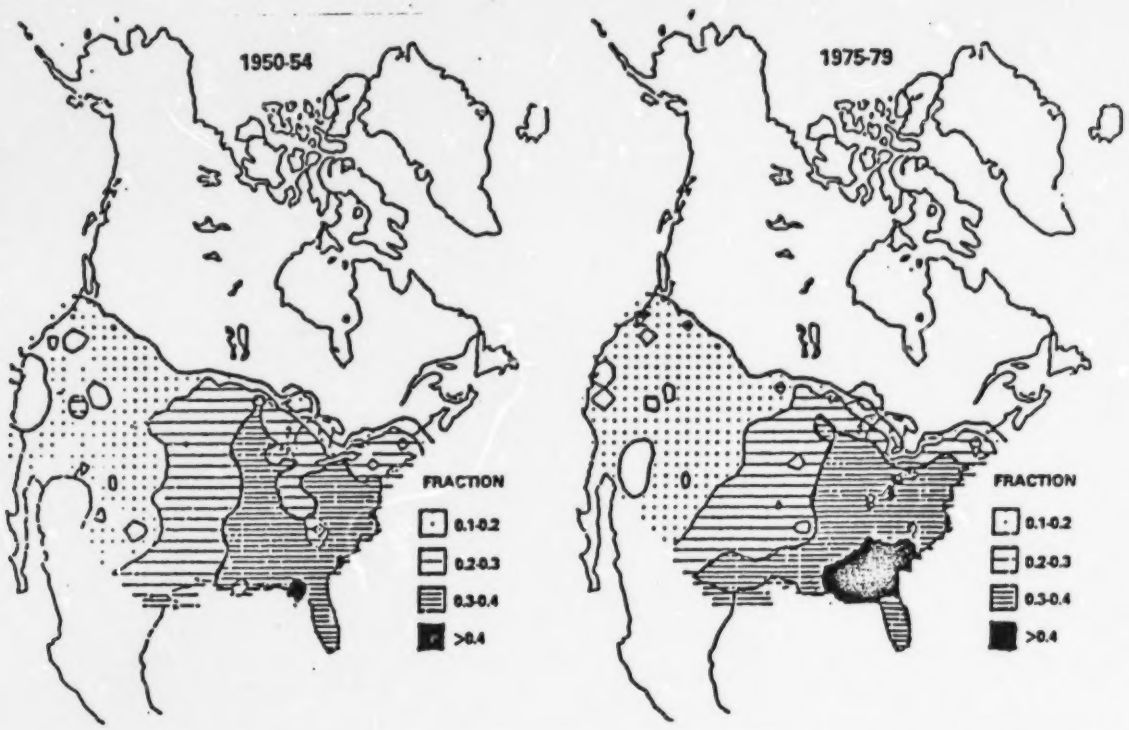

Fig. 9. Noon low level cloud cover. Summer season. Low level cloud data for Canada is not available (3rd quarter)

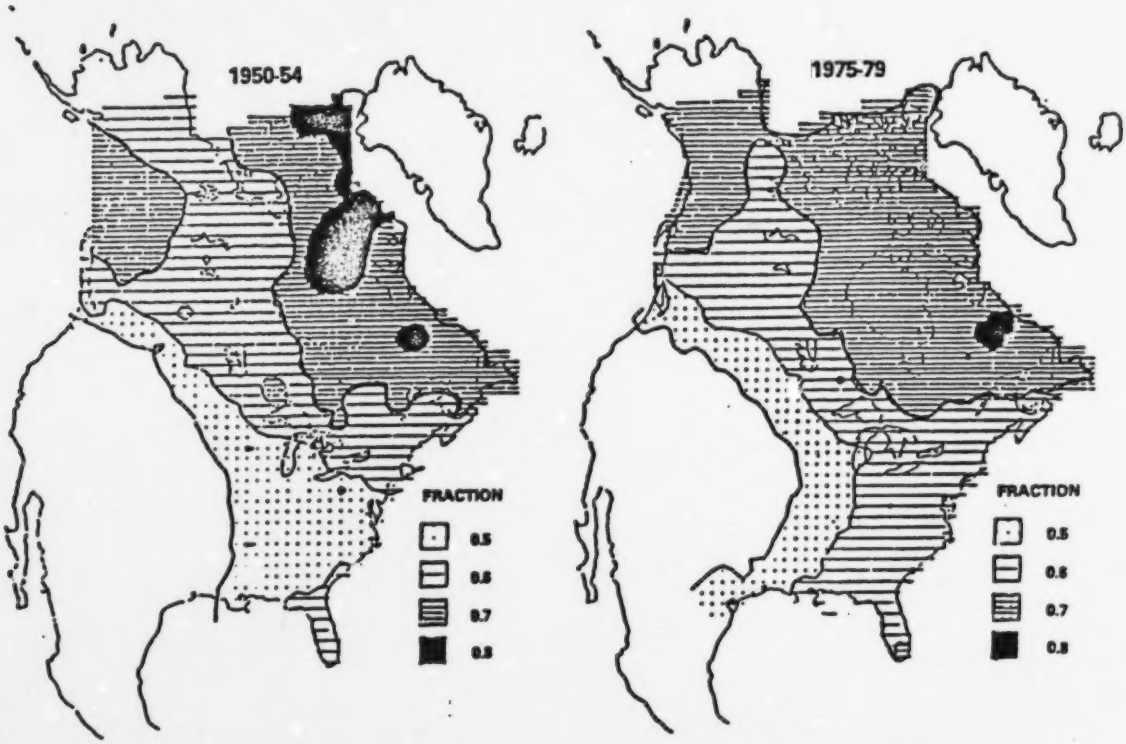

Fig. 10. Noon total cloud cover. Summer season. (3rd quarter)

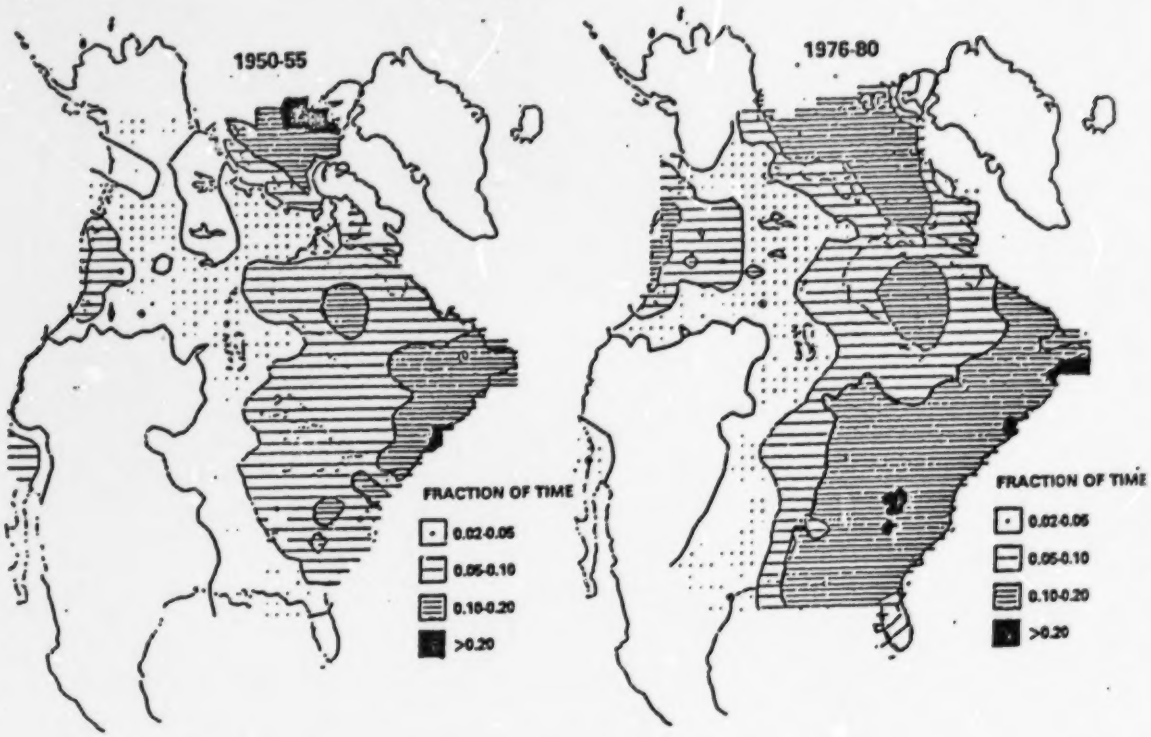

Fig. 11. Fog observations for summer seasons. (3rd quarter)

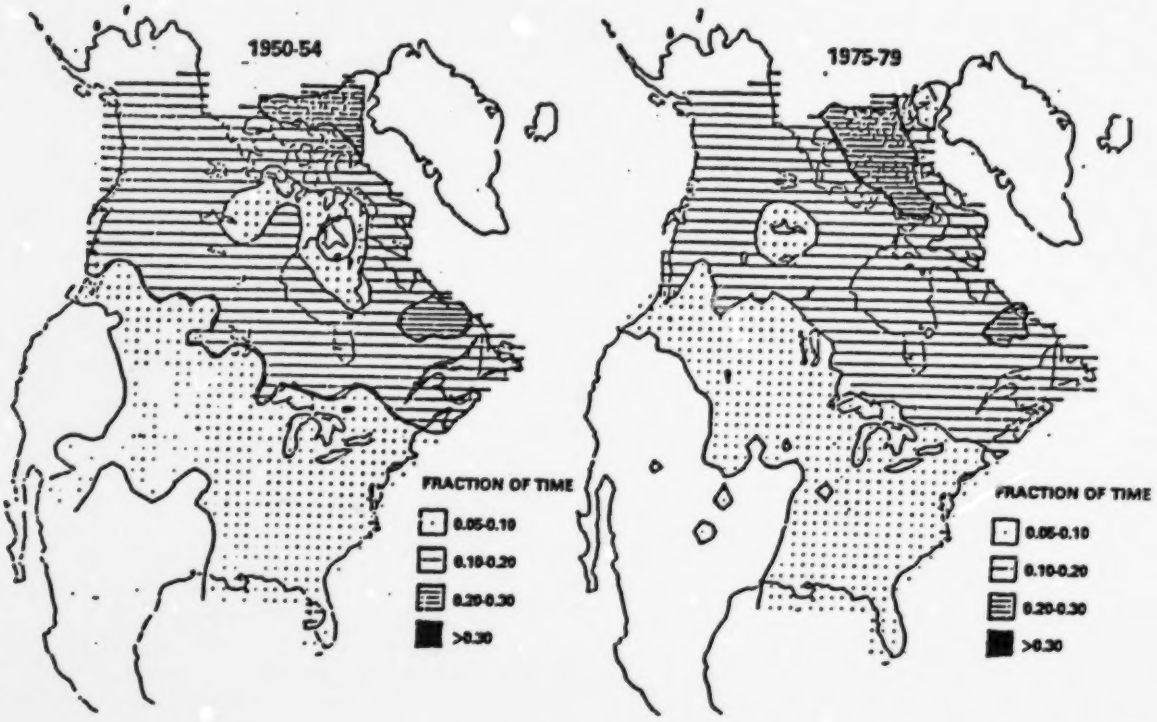

Fig. 12. Fraction of time with precipitation for summer season (3rd quarter)

(<5% of the time). The eastern U.S. raininess does not show a significant secular trend.

A potential cause of secular climatic trends is a change in the regional scale circulation pattern. Currently we do not possess a convenient measure of the regional moisture and heat transport field. A possible surrogate for this purpose is the sea level pressure field depicted in Fig. 13. The main features of the North American pressure field were similar in the 1950's and 1970's, although there was a slight increase of the eastern U.S. average from 1016.7 to 1017.3 mb. It is unclear whether this magnitude of pressure change might be responsible for the observed temperature, moisture and cloud cover trends.

The increase in turbidity observed during the decades 1960 and 1970 is paralleled by an increase in haziness as indicated by human observer measurement of visibility distance at airport weather stations. Increases in relative humidity caused aerosol particles to increase in size increasing the light scattering. Thus the increase in turbidity and haziness could be attributed to the increase in relative humidity. It is possible to adjust the light scattering, inferred from visibility distance measurements, to a standard relative humidity. When the scattering is corrected to 50% RH as shown in Fig. 14 (Husar et al., 1979), there is clearly an increase in total fine particle loading. Therefore, it seems reasonable to look for mechanisms by which an increase in fine particle pollution could lead to the observed changes.

SUMMARY AND CONCLUSIONS

To summarize the findings, comparisons on data from 1950-54 and 1975-79 indicate a reduction in eastern U.S. noon surface temperature of over 1^{o}C (no change in western U.S. and Canada) and an increase in midnight temperature. The areas of climatic change coincide with the area of increased aerosols in the atmosphere. Also, there have been changes in the dew point from 16.7 ^{o}C to 18.0 ^{o}C and an increase in relative humidity from 54.5% to 60.5% for the eastern U.S. During the same period, there has been an increase in cloud cover in the lower layer of the atmosphere (the same layer where haze occurs) of 30% to 35%. Fog frequency doubled from 7% to 14%, and total noontime cover increased about 5%, from 58% to 63%. Though there was no observable change in frequency of precipitation, there was some increase in the summertime pressure field, thus bringing in more moisture. In sum, there is a consistent data base showing climatic changes in the eastern U.S. These climatic changes correspond in space and time to increased haziness. The challenge is to justify scientifically the attribution of these climatic changes to the increase in the amount of haze in the region.

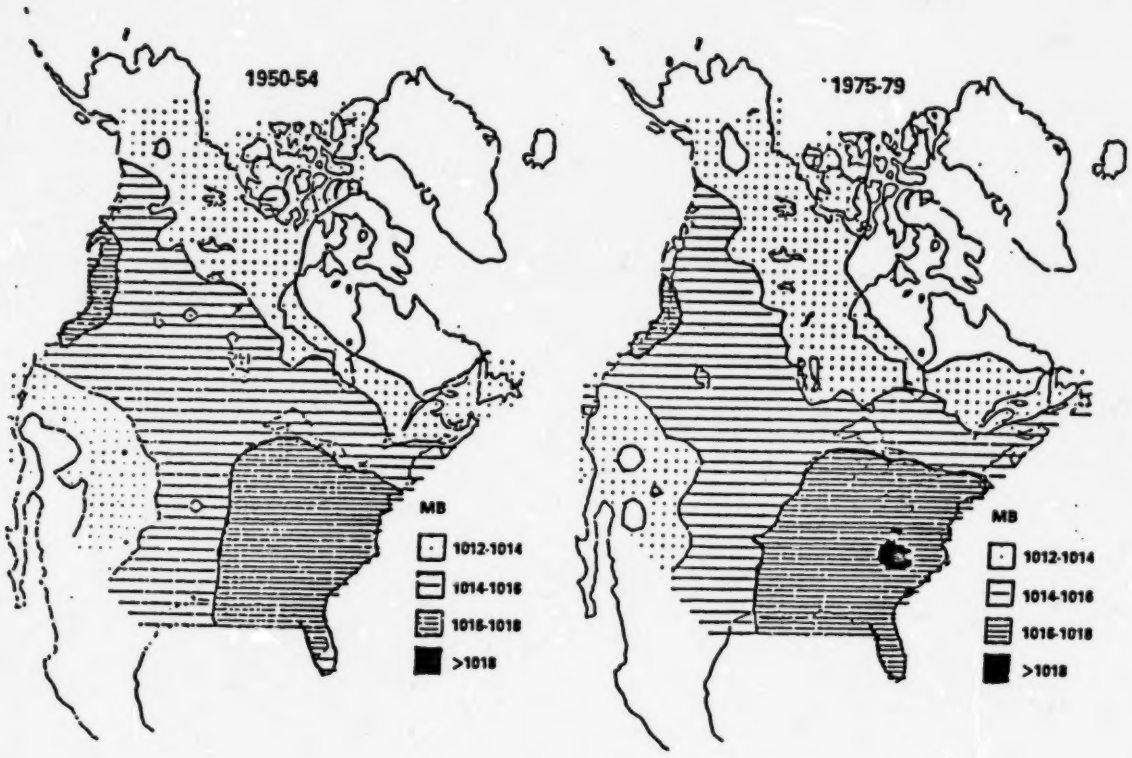

Fig. 13. Noon sea level pressure field for summer season (3rd quarter)

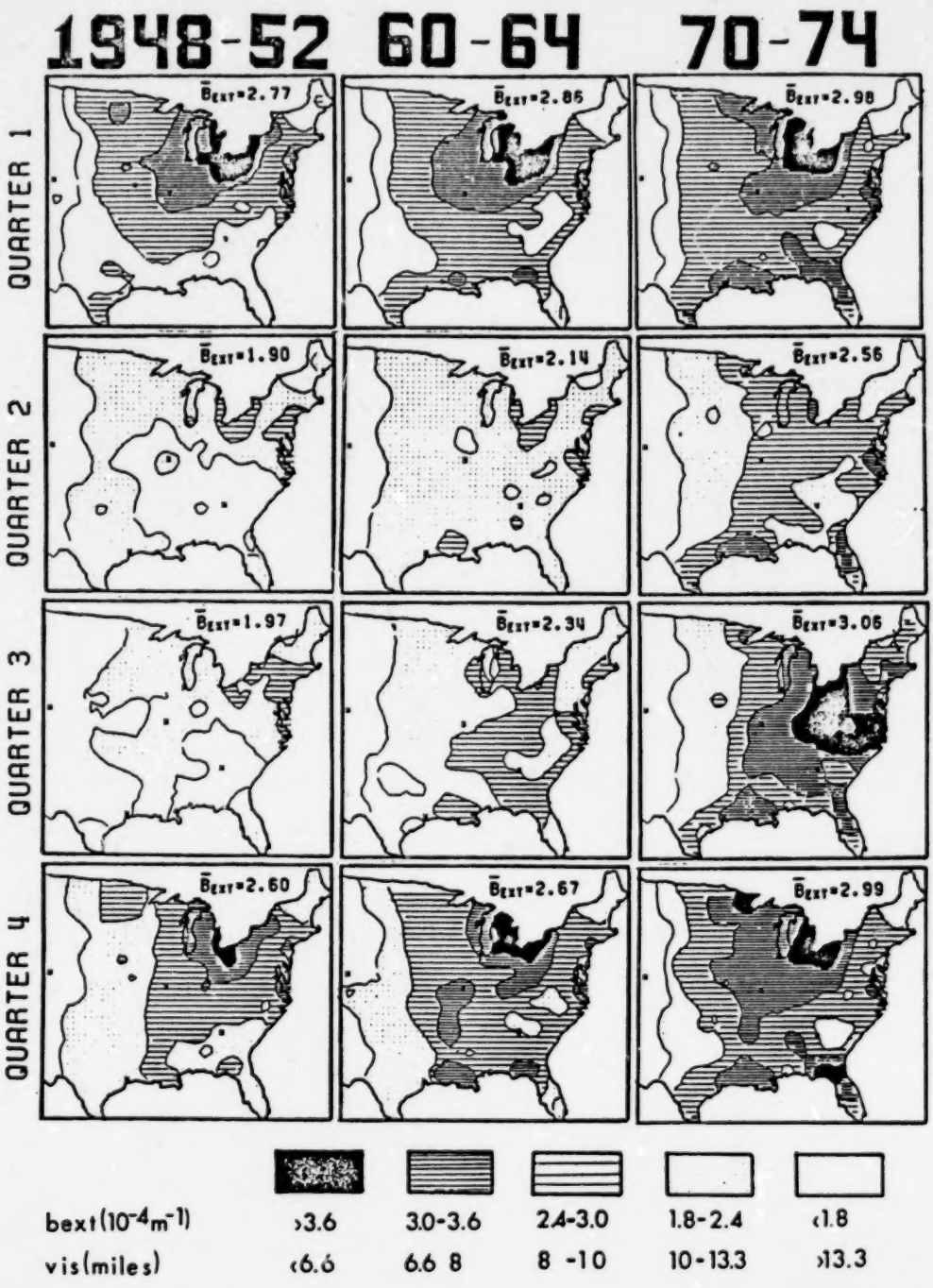

Fig. 14. The spatial distribution of five-year average extinction coefficients show the drastic increases of quarter 3 extinction coefficients in the Carolinas, Ohio River Valley, and Tennessee-Kentucky area. In the summers of 1948-1952, a 1000 km size multistate region centered around Atlanta, Georgia, had visibility greater than 15 miles, which has declined to less than 8 miles by the 1970's. The spatial trend of winter (quarter 1) visibility shows improvements in the n.E. megalopolis region and some worsening in the sunbelt region. Both spring and fall quarters exhibit moderate but detectable increase over the entire eastern U.S..

In the course of this work, although not presented here, we have examined the trends of several other meteorological parameters such as the demodulation of the diurnal RH changes, regional shifts in the RH and temperature distribution functions, etc. and they were consistent with the demodulation of the daily temperature fluctuations. We are also aware of works which state that an increase in aerosol loading could change the regional microclimate (e.g. Robinson et al., 1976) or global atmospheric temperature (e.g. Bolin and Charlson, 1976). Angell and Korshover (1975) also reported substantial decreases in the total hours of solar radiation over the southeastern U.S., which could be due to "delaying sunrise" and "advancing sunset" (from the point of view of an on-off solar radiation detector). We are also aware of the fact that most of these observed anomalies could be due to an increase of daytime cloudiness, which may or may not be related to human activities. The robust nature of the planetary atmosphere, with its numerous apparent and hidden feedback mechanisms, also provides a warning. Hence, prudence dictates that with our current experience and capability we do not claim any conclusion as to whether the observed climatological changes over the east central U.S. are primarily due to an increase in anthropogenic haziness. Nevertheless, these trends contribute to the appeal of the genesis strategy (Schneider 1976).

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